Characterization and Performance Improvement of Machining Systems

Program Manager: M Alkan Donmez
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Goal

To provide U.S. industry with the measurement methods, standards, models, data analysis tools, error compensation, and closed-loop machining methodologies necessary to monitor, assess, describe, control, and improve the performance of machining systems used for discrete-part manufacturing. To provide leadership in the development of machine tool performance evaluation standards, including harmonization between national and international standards.

Program Objectives

FY2000

Provide technical expertise and leadership in national and international machine tool related standards.

Technical Support for Machine Tool Characterization Standards

Develop, test, and verify new machine tool performance evaluation methods and equipment in support of national and international machine tool standardization efforts.

FY2000

Complete implementation of the previously developed closed-loop machining algorithms based on pre-process, process-intermittent, and post-process measurements and feedback.

System Integration for Closed-Loop Machining

Complete implementation of closed-loop machining algorithms by integrating three control layers (real-time, process-intermittent, and post-process).

FY2002

Develop and assess methods for characterization of geometric, thermal, dynamic, contouring, and loaded performance of machine tools.

Design of Thermal Enclosure for Machine Tools

Design and develop a thermal enclosure system to minimize thermal deformations of machine structural components by providing a uniform thermal environment using machine's own safety enclosure.

FY2002

Develop information technology infrastructure for machine tool performance data management.

Development of Machine Tool Data Dictionary and Performance Data Repository

Develop standardized data specification for machine tool performance evaluation tests and web-based data repository.

Data Management for Closed-Loop Machining

Develop and apply part feature concepts, data formats, data generation tools, and database functions to facilitate efficient monitoring and control of closed-loop turning processes.

FY2002

Develop techniques for performance characterization and improvement of parallel kinematic machine tools.

Performance Evaluation of Parallel-Linkage Machine Tools

Develop models, parameters, and test methods to assess, describe, and improve the performance of parallel-linkage machine tools.

FY2003

Develop deterministic and non-deterministic error models, robust compensation methodologies, and high fidelity simulation systems for machine tools.

Uncertainty Analysis

Develop machine performance simulation applications integrating performance uncertainties into machine models.

FY2003

Develop methods and procedures to assess the capabilities of new and existing machine tool metrology equipment, software, and algorithms.

Testing Algorithms for the Performance Evaluation of Machine Tools and Coordinate Measuring Machines (CMMs)

Explore both the need for, and realization of, an efficient means to test the software that is used to assess and analyze machine CMM performance.

FY2004

Develop methods and procedures to characterize and predict the performance parameters of machine tool subsystems including spindles, drive systems, slides, rotary tables, bearings, controllers, tool changers, and pallet changers.

Development of Linear Motor Testbed

Develop a testbed to investigate measurement methods and key performance characteristics of linear motors used in high-speed machine tools.

FY2004

Develop sensing and analysis capabilities for machine tool monitoring and diagnostic methods to optimize performance and to identify potential machine failure modes and corrective actions.

Simulated Accelerated Life for Machine Tool Components

Develop and demonstrate methods to simulate accelerated life testing for machine tool components to improve machine tool monitoring and condition-based maintenance (CBM) capabilities.

FY2004

Develop generic predictive maintenance algorithms for cost-effective maintenance of machining systems, including subsystems and auxiliary equipment.

FY2005

Develop performance characterization methods and procedures and process control methodology for machines used for micro/meso-machining as well as solid freeform fabrication.

Customer Needs

To compete effectively in global markets, U.S. industry needs to manufacture high-precision products consistently and at competitive costs. This requires a high degree of control over manufacturing processes, including machines, tooling, and inspection systems used in manufacturing. As indicated in the latest. Integrated Manufacturing Technology Roadmapping (IMTR) effort, the future of manufacturing lies in the usage of flexible machine tools operated in a closed-loop environment to always deliver the correct product. In such an environment characterization and modeling of performance of these machine tools and other supporting equipment are essential.

Machine tools are critical elements in discrete part fabrication, which represents about 30 % of the overall discrete part manufacturing operations in the US. The principal users of machine tools are job shops, the aerospace, defense, and automotive industries, producers of construction, agricultural, industrial, and electrical machinery, and the home appliance industry. Most machine tools in the U.S. are bought on the basis of the reputation of the manufacturer, personal contact, or cutting tests rather than performance specifications based on machine metrology procedures. Many users feel that the existing tests by the manufacturers do not reflect their needs and request customized tests focused on the intended application of the machine. The results are high costs, interpretation difficulties, and disagreements, and often the selection of the wrong machine for a particular application. Furthermore, lack of machine tool characterization means that the user often has incomplete knowledge of the true capability of a particular machine, and of the machine's performance variability with use, both of which lead to increased cost and lead time in production.

Manufacturers need to assess the capability of machine tools to select the most appropriate machine for a given job, to assure that machined parts conform to the design specifications, to determine the causes of observed part errors and develop corrective actions, and to enable predictive maintenance. They also need to assure compliance with quality management standards, which require periodic tests of the accuracy of machines used in production. In addition, machine tool builders and users need a mutually acceptable set of specifications and methods of verification and performance comparison among machines.

Machine tool characterization is difficult because there are many geometrical, thermal, and dynamic sources of error whose effects on part accuracy are complex. Current test methods are elaborate, time consuming and require a high degree of metrology expertise. The resulting performance parameters are difficult to translate into part tolerances obtained under real cutting conditions. The situation is further complicated by the lack of harmonization in both the terminology and

APTD researchers communicating machine testing information via Web and analyzing ballbar data on the Web.

data analysis tools used in various national and international standards.

Improving machine tool performance is critical to improving the overall precision and performance of manufacturing towards meeting the continuously tightening market demands. Tighter tolerances are required for interchangeability, automatic assembly, miniaturization, integration, design simplicity, and improved performance and reliability. The Association for Manufacturing Technology (AMT) Technology Roadmap for the Machine Tool Industry targets a 70 % improvement of machine tool accuracy between 1995 and 2005. Improved performance evaluation and error compensation techniques will play a critical role in reaching that goal. Development of machine performance models that are simple, reliable, and robust is a crucial task to achieve cost-effective error compensation.

In summary, this program supports a broad spectrum of manufacturing industries, including aerospace, automotive, machine tool, and heavy equipment manufacturers, as well as small manufacturing enterprises that provide machining support to these large industry groups.

Technical Approach

This program is a combination of research and development, as well as national and international standards development efforts, related to machine tool characterization, performance evaluation, and improvement. Machine tools exhibit a complex set of errors including geometric, thermally-induced, static- and dynamic-load-induced, controller-induced, and environment-related errors. The performance of machine tools is influenced by the interaction of these errors with different magnitudes and time constants. In the last decade, the National Institute of Standards and Technology (NIST) has been very active in developing methodologies for machine tool performance characterization and real-time error compensation based on predicted machine performance, which resulted in order of magnitude improvements in machine tool performance. But, proper machine tool characterization is a time-consuming, non-production activity that requires a high level of machine metrology expertise, and therefore creates a significant burden to manufacturers. More research, development, and standardization are needed to make machine tool characterization and error compensation practical solutions for industry.

Our experience and the results of other efforts published in the literature indicate that existing machine tool error models are not easily transferable between similarly designed machines and that these models do not predict the machine behavior very well if the machine environment has changed. Therefore, one of our research priorities is the development of simple and robust first-order models for machine tool errors and the implementation of error compensation based on these models for a variety of machines and industrial settings. We will collect performance data from a variety of machine tools in a variety of manufacturing environments to develop and test such models. The other strong areas of our current research and development are performance evaluation of turning centers, machining centers, and new generation parallel-linkage machine tools; improving equipment and methods of machine tool metrology; and evaluation of machine tool spindles. To respond to the industry need to minimize the time required for the machine tool characterization, we are evaluating new machine tool metrology equipment such as two-dimensional grid encoders and laser-based ballbars. We are developing testing algorithms to evaluate software used in such instruments. Our goal is to assess the needs for development of an algorithm testing service for machine tool performance evaluation software.

The sources of errors that are the focus of the future activities include static and dynamic-load-induced errors and controller-related errors, including dynamic contouring errors that are caused by the interactions between the controllers and machine structural properties. New methodologies will be developed to determine the results of those errors and these methods will be proposed for incorporation into the new versions of machine tool performance standards. As a part of this activity, performance of machine tool controllers, drive systems, and motion controllers will be tested. A testbed has already been developed to evaluate motion control boards. It will be used extensively to compare the performance of different motion control boards and control algorithms. A linear motor based high-speed drive system will be developed to investigate the challenges introduced by the new high-velocity machine tools that are appearing on the market. The characterization of such machine tool subsystems, including spindles, bearings, and drive systems will aid machine tool designers in selecting certain components for certain desired machine tool performance criteria.

One objective of machine performance characterization is to translate this information into the tolerances of machined parts. We will investigate the effects of average parametric errors and their variances on the variances of part dimensions. The law of propagation of uncertainties will be used to estimate the final uncertainty in the error estimates between the cutting tool and the workpiece. We will establish methods to estimate part variances from performance data and validate such methodology using cutting tests.

Another important objective of this program is to implement various closed-loop machining algorithms and improve upon the multilayer control architecture for machining that has been designed and tested over the past decade. Closed-loop machining - a systematic approach in which information obtained during, in between, and after machining operations is used in feedback loops to control the quality of machined parts - is predicated upon the premise that, in an automated environment, machine tools perform in a sufficiently deterministic manner to allow quality assurance through control of the process rather than inspection of the machined part. Process control is most cost-effective if it can be achieved without spending too much time and effort developing models for the processes and equipment. This requires simple tunable, self-learning models and control algorithms. One result of this effort will be the identification of measurements and standards needs for machining process verification or validation as opposed to product verification. This effort will lead to the identification of measurements and standards needs for machine tool diagnostics and predictive maintenance, which is one of the most critical components of the cost-effective manufacturing as identified in the Machine Tool Technology Forum organized last year by the Association for Manufacturing Technology (AMT). Newly developed smart sensors and interfaces will be implemented and tested on our machine tools as part of this effort.

With the proliferation of machine tool performance data, efficient and distributed access to such information becomes crucial in capacity planning and machine tool selection. A critical enabler to the efficient storage and exchange of performance data is a unified information model for the performance tests. In collaboration with the manufacturers and users of machine tool test equipment, we are developing definitions for the relevant data elements and their relations. The information model includes a description of the test procedure, the test conditions, the characteristics of the equipment used, the measurement set-up, and the test results. A prototype web site that allows users at distributed sites to share, store, compare, and analyze performance test data will demonstrate the potential use of such an information model.

In the long run, the knowledge and experience gained from these efforts will be applied to new manufacturing technologies, such as micro/meso-manufacturing and solid freeform fabrication. In addition, the information obtained about the machine tools over a long period of time will allow us to develop robust statistical techniques for estimation of process capability and machine or machining uncertainty. Based on these statistical and deterministic characteristics, realistic virtual machining simulations will be developed. The outcome of these simulations will be the realistic representation of machined parts with predicted dimension, form, and finish errors built in. These models will be used in broader virtual prototyping systems that product design teams can use as design tools.

Finally, this program is aimed at transferring the research results immediately to standardization activities. To achieve this objective, we are continuously involved in the activities of the relevant standards committees at the national and international levels. We introduce the results of our measurements and evaluations to develop and validate the methods that are incorporated into the standards. This program interacts synergistically with several other programs within the Manufacturing Engineering Laboratory, such as the "Predictive Manufacturing," "Sensors, Interfaces, & Networks for Metrology & Manufacturing," and "Intelligent Open Architecture Control of Manufacturing Systems."

Standards Participation

- American National Standards Institute (ANSI)/ American Society of Mechanical Engineers (ASME) B5: Machine Tools
- ANSI/ASME B5 TC52: Performance Evaluation of Machine Tools
- ANSI/ASME B5 TC56: Information Technology for Machine Tools
- ANSI/ASME B89.3.4: Axis of Rotation
- Electronic Industries Association (EIA)/ Industrial Engineering (IE) 31: Numerical Control
- ISO Technical Committee (TC) 39: Machine Tools
- ISO TC184 Sub-committee (SC) 4: Industrial Data
- ISO TC184 SC4 Working Group (WG) 3: Product Modeling
- ISO TC39 SC2: Test Conditions for Machine Tools, Secretariat
- ISO TC39 SC2 WG1: Revision of ISO 230-1
- ISO TC39 SC2 WG3: Test Conditions for Machining Centers
- ISO TC39 SC2 WG6: Thermal Effects of Machine Tools, Convener
- ISO TC39 SC6: Noise of Machine Tools

Accomplishments

- September FY1999 Published approximately 50 papers and technical reports to-date describing related research.
- September FY1999 Continued participation in the national and international machine tool standards committees, provided Secretariat functions for ISO/TC39/SC2 "Test Conditions for Machine Tools", drafted documents and organized meetings twice a year. Continued maintaining 60 international machine tool standards.
- September FY1999 Completed a draft of the "Data Specification for Machine Tool Performance Tests." The specification defines the properties and results of machine tool performance tests to form the basis of a common presentation. The draft covers most of the machine tool performance tests mentioned in the ANSI/ASME B5.54 and B5.57 standards.
- September FY1999 Completed a comparative study of variety of national and international positioning accuracy standards for machine tools to assess the differences in the positioning accuracy definitions among these standards (VDI, JIS, B5.54, B5.57, ISO 230-2:1988, and ISO 230-2:1997).
- September FY1999 In collaboration with industry, carried out testing of a laser-based circular testing instrument and a long-range ballbar system currently under development by industry.
- August FY1999 Initiated a collaborative study with Ford Motor Company and the University of Illinois on the application of parallel-linkage machine tool technology to automotive manufacturing. This study includes an extensive set of performance tests on several types of parallel machines.
- January FY1999 Developed and tested several techniques to assess, model, and compensate the geometric and thermal errors of a hexapod machine tool. Implemented geometric error compensation and demonstrated a factor of 5 improve-

ment. Developed techniques for uncertainty analysis and error budgeting of hexapod machine tools. Developed virtual machining software for the hexapod.

- January FY1999 Having established an industry consortium in1999 to obtain guidance for the development of the machine performance data repository. Developed information models for machine circular tests, developed a corresponding database schema, and implemented it as a web based prototype machine performance data repository. Incorporated performance tracking and trend analysis graphics into prototype web repository. Organized five workshops and two teleconference meetings attended by industry and academia related to this effort.
- January FY1999 Provided technical guidance for the development of a commercial software package to model machine tool geometric errors and simulate machined part geometry.
- January FY1999 Based on a new work item initiated in 1996 to develop international standard for thermal evaluation of machine tools, developed draft and facilitated its acceptance as the Draft International Standard (ISO/DIS 230-3).
- January FY1999 Upgraded the Coordinate Measuring Machine (CMM) operating system and integrated it into the quality control system. Developed MATLAB routines to perform and test post-process analysis and control algorithms and carry out experimental validation on the turning center.
- January FY1999 Initiated a preliminary investigation to minimize dimensional variations in camshaft grinding.
- January FY1999 Initiated a study to explore both the need for, and realization of, an efficient means to test the software that is used to assess and analyze machine tool and CMM performance. This pilot study focuses on the software used to calculate and diagnose the results of the popular circular contouring tests. Two software functions are tested: 1) calculation of standardized performance parameters, and 2) estimation of machine tool error sources.
- January FY1998 Developed and tested generic process-intermittent control algorithms using a feature-based inspection strategy and B-spline curve fitting techniques to measure and correct for part dimension and form errors in real-time. Developed a database to collect information about the machine tool, process, and machined part. This database is used as a major tool for verifying and improving machine tool models via closed-loop machining algorithms.
- September FY1997 In collaboration with the Massachusetts Institute of Technology (MIT) and Landis Corporation, received the R&D 100 award for developing a machine variability analysis of camshaft grinding process.
- January FY1997 Analyzed the error motion, stiffness and thermal characteristics of roller bearing spindles and modified standardized data acquisition and analysis methods. The findings were part of the driving force behind the current effort to revise the US national standard on axis of rotation.
- January FY1997 Developed and implemented three-layer control architecture to carry out process control for turning using three different control cycles (real-time, process-intermittent, and post-process).
- January FY1997 Developed algorithms using clustering, trend, and deviation analyses to determine conditions in which the actual machine performance deviates from the expected performance. Developed high-speed data acquisition system, which includes signal-processing utilities such as Fast Fourier Transform (FFT), power spectrum, and histogram functions to be used in machine tool diagnostics.